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QUANTIFYING COCOA CROP WATER REQUIREMENTS IN SABAH, MALAYSIA TO SUPPORT PRECISION IRRIGATION

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ABSTRACT – *This research explores the crop water requirements (CWR) of cocoa (Theobroma cacao) using the FAO-56 Penman-Monteith method to estimate reference evapotranspiration (ETo). Precise calculation of CWR is essential for improving irrigation efficiency, particularly in regions like Sabah, Malaysia, where cocoa farmers are increasingly affected by unpredictable weather and poor water management. The study focuses on two major cocoa-producing areas in Kota Kinabalu and Tawau. Climate data such as temperature, humidity, wind speed, and solar radiation were collected from the FAO CLIMWAT 2.0 database and processed using FAO CROPWAT 8.0 software. ETo values were then used alongside crop-specific coefficients (Kc) to determine the crop evapotranspiration (ETc) of cocoa at its fully developed stage. The results showed similar ETo and ETc patterns across both regions, with no statistically significant difference between them ($t(11) = 1.72$, p-value = 0.116, $\alpha < 0.05$). The estimated irrigation need ranged from 35 to 44 L tree^{-1} day^{-1} for 3 x 3 meter planting spacing throughout the year with no interference from rainfall. These findings emphasize the need for irrigation strategies that are tailored to local conditions while maintaining overall consistency, supporting more efficient water management. Integrating such data-driven approaches into precision agriculture can help reduce water waste, maintain soil moisture balance, and enhance crop productivity, thereby improving the resilience and sustainability of cocoa farming systems in Sabah.*

Keywords: Crop water requirement (CWR), Penman-Monteith method, evapotranspiration, precision agriculture, cocoa

INTRODUCTION

Cocoa Plantations in Sabah, Malaysia

Cocoa (*Theobroma cacao*) plays a vital role in the agricultural landscape of Sabah, Malaysia, supporting local economies and the livelihoods of smallholder farmers. The region's tropical climate is generally favorable for cocoa cultivation. However, recent years have seen increased challenges due to unpredictable climate conditions. Prolonged dry spells and sudden intense weather events have led to water stress which reduced yields and caused difficulties in plantation maintenance. These issues are compounded by the limitations of traditional irrigation practices, underscoring the need for more sustainable and adaptive water management strategies.

Irrigation Methods for Cocoa Plantations

Most commercial cocoa plantations in Sabah still rely on conventional irrigation methods, which apply water on fixed schedules rather than responding to actual plant needs. This results in inefficient water use and increased vulnerability to climatic variability. According to previous studies, drought stress occurs when water loss through transpiration exceeds the tree's capacity for water absorption, leading to disruptions in physiological processes and limitations in tissue growth (Adet *et al.*, 2024). As a response, precision agriculture has emerged as a promising alternative by leveraging data and technology to optimize agricultural inputs. The cocoa plant is irrigated using methods such as sprinklers, micro-drip irrigation and micro-sprayer systems depending on the growth stage of the crop. Each growth stage requires an adequate water supply to support optimal plant development. Designing a plant watering system tailored to crop water needs is challenging as it requires the consideration of multiple interrelated factors simultaneously (Hanif *et al.*, 2024). One of its key components is crop water requirement (CWR) estimation which enables site-specific irrigation planning. Incorporating CWR into cocoa cultivation can significantly enhance water use efficiency, reduce waste, and improve crop health and productivity.

Crop Water Requirement (CWR) for Cocoa

Crop water requirement (CWR), also known as crop evapotranspiration (ETc), represents the total amount of water needed by a crop to grow optimally without experiencing water stress. It is influenced by climatic, soil, and crop-specific factors. The FAO-56 Penman-Monteith method originates from the foundational work of Penman (1940) and subsequent refinements introduced by Monteith (1960) (Allen *et al.*, 2002) is widely recognized for estimating reference evapotranspiration (ETo), which is the foundation of CWR calculations. This method uses environmental data, including temperature, humidity, solar radiation, and wind speed, to generate a reliable estimate of a crop's water demand, which is then adjusted using crop coefficients (Kc) relevant to cocoa at various growth stages.

Integrating the FAO-56 Penman-Monteith method into cocoa irrigation management facilitates precise and adaptive water application. This can mitigate the impacts of climate variability by aligning irrigation with real-time plant needs. Unpredictable weather patterns remain a significant factor affecting the effectiveness of agricultural interventions aimed at enhancing food production, often reducing their reliability and consistency under field conditions (Amarkai & Süheri, 2024). The anticipated benefits include reduced operational costs, improved yield, enhanced fertilizer efficiency, and increased sustainability. Furthermore, this approach contributes to water conservation, promotes technological advancement in agriculture, and supports climate-resilient farming practices. Thus, the application of CWR within a precision agriculture framework represents a strategic advancement toward efficient and sustainable cocoa production in Sabah.

Impact of Water Stress

The cocoa plant is highly sensitive to both insufficient and excessive water. When soil moisture drops below 70%, cocoa plants often experience stress, leading to stunted growth and reduced yield quality. On the other hand, when moisture levels go beyond 85%, problems such as poor soil aeration and root diseases can develop, affecting nutrient uptake and plant health (Ortega *et al.*, 2024). These challenges make it critical to optimize irrigation to deliver just the right amount of water, avoiding extremes that can compromise both yield and quality.

Cocoa Growth Stages

Determining how much water cocoa plant needs throughout its growing period involves more than just one static figure. Different growth phases require different amounts of water, and this is reflected in changing crop coefficient (Kc) values. For example, early-stage cocoa plants generally need less water, while mature plants with full canopies lose more moisture through evaporation and transpiration, thus requiring higher Kc values (Suhartanto & Safitri, 2020). A study in Yogyakarta revealed that cocoa had a low crop water productivity (CWP), with just 0.037 to 0.059 kg of dried beans produced per cubic meter of water. This low figure points to inefficiencies in water use and underscores the need for precision irrigation methods to improve land and water productivity.

Water Management Strategies

A study conducted in Bahia, located in eastern Brazil, emphasizes the broader significance of accurately managing crop water requirements. The research revealed substantial variability in the water scarcity footprint of cocoa irrigation across different municipalities, highlighting the importance of localized assessments. This variation indicates that sustainable water resource management, particularly in regions facing water limitations, requires site-specific approaches. The integration of local climatic conditions, soil characteristics, and crop-specific water demand is therefore essential to develop efficient and balanced irrigation strategies (Olegário *et al.*, 2022).

Therefore, the objectives of this study are (1) to estimate the crop water requirement (CWR) for fully developed cocoa plants by utilizing the FAO CROPWAT 8.0 model, which integrates climatic data derived using the FAO-56 Penman-Monteith method, and (2) to compare the crop evapotranspiration (ETc) values between two major cocoa-growing regions in Kota Kinabalu and Tawau both in Sabah, Malaysia.

MATERIALS AND METHODS

Study Area

This research was conducted in two significant cocoa-producing regions in Sabah, Malaysia: Kota Kinabalu and Tawau. These locations were strategically selected due to their active involvement in cocoa cultivation and their contrasting climatic profiles, which provide a comprehensive basis for evaluating regional variations in crop water requirements. Kota Kinabalu is located on the northwest coast of Sabah at coordinates 5.93°N latitude and 116.05°E longitude, with an elevation of approximately 3 meters above sea level. The region experiences a tropical rainforest climate characterized by consistently high humidity, stable temperatures, and moderate rainfall distributed throughout the year.

Conversely, Tawau is situated on the southeastern coast of Sabah, positioned at 4.26°N latitude and 117.88°E longitude, with an altitude of around 20 meters. This area typically receives higher annual precipitation and is more susceptible to climatic extremes, including prolonged dry spells and intense rainfall events. These climatic differences between the two regions make them suitable for comparative analysis of evapotranspiration patterns and their impact on cocoa crop water needs.

Climatic Data

To calculate reference evapotranspiration (ETo) for the cocoa crop water requirement analysis, this study employed climate data obtained from the FAO CLIMWAT 2.0 database. The FAO CLIMWAT 2.0 provides observed agroclimatic data, typically spanning 1971–2000, with some series extending outside this range if they meet the minimum 15-year duration and end after 1975 with more than 5000 meteorological stations distributed across various regions worldwide (Food and Agriculture Organization of the United Nations [FAO], n.d.). It offers long-term average monthly climatic records derived from a global network of weather stations and is intended to work alongside the FAO's CROPWAT 8.0 software for irrigation and water resource planning (Food and Agriculture Organization of the United Nations [FAO], 2021). For this research, climate stations representing two major cocoa-producing areas in Kota Kinabalu and Tawau were selected.

These locations not only reflect the regional diversity of cocoa cultivation in Sabah, Malaysia, but also offer valuable contrasts in climatic conditions. These coordinates were used to align the study with the closest available CLIMWAT 2.0 data sets and to ensure that the environmental context of cocoa plantations in these areas was accurately represented. Tables 1 and 2 show data collected, including monthly averages for temperature, humidity, wind speed, and sunshine hours from respective stations. These climatic inputs are fundamental to the FAO-56 Penman-Monteith model, which is the standard for computing ETo.

Table 1: Average climate characteristics recorded by Kota Kinabalu weather station, CLIMWAT 2.0.

Month	**Min. temperature (◦C)**	**Max. temperature (◦C)**	**Humidity (%)**	**Wind (m s^{-1})**	**Sun (hours)**	**Radiation (MJ m^{-2} day^{-1})**
Jan	22.7	29.8	84	1.8	6.2	17.4
Feb	22.7	30.1	87	1.8	6.8	19.3
Mar	23.3	30.9	82	1.7	7.3	20.8
Apr	23.9	31.6	81	1.7	8.0	21.8
May	24.1	31.7	82	1.8	7.0	19.6
Jun	23.8	31.3	80	2.0	6.5	18.4
Jul	23.5	31.0	80	2.2	6.6	18.6
Aug	23.5	31.1	83	2.3	6.3	18.7
Sep	23.5	30.9	81	2.3	6.0	18.6
Oct	23.4	30.8	83	2.3	6.5	18.9
Nov	23.3	30.6	84	2.1	6.3	17.7
Dec	23.1	30.4	83	1.9	6.4	17.3
Average	**23.4**	**30.9**	**83**	**2.0**	**6.7**	**18.9**

Table 2: Average climate characteristics recorded by Tawau weather station, CLIMWAT 2.0.

Month	**Min. temperature (◦C)**	**Max. temperature (◦C)**	**Humidity (%)**	**Wind (m s^{-1})**	**Sun (hours)**	**Radiation (MJ m^{-2} day^{-1})**
Jan	22.4	31.6	86	1.4	5.9	17.2
Feb	22.3	31.4	85	1.4	6.6	19.1
Mar	22.6	31.9	84	1.7	7.0	20.3
Apr	23.1	32.3	84	1.8	7.4	20.8
May	23.5	32.4	85	1.7	7.5	20.0
Jun	23.3	31.8	85	1.6	6.4	17.9
Jul	22.8	31.3	86	1.6	7.0	18.9
Aug	22.9	31.5	85	1.7	7.1	19.8
Sep	22.7	31.7	85	1.6	6.6	19.5
Oct	23.0	31.9	85	1.5	6.4	18.9
Nov	23.0	32.0	85	1.4	6.4	18.2
Dec	22.6	31.9	85	1.4	6.3	17.4

Average	**22.9**	**31.8**	**85**	**6.7**	**6.7**	**19.0**

Reference Evapotranspiration (ETo) Calculation

To determine reference evapotranspiration (ETo), this research applies the FAO-56 Penman-Monteith equation (Allen et al., 2002), which incorporates multiple climatic parameters that influence evapotranspiration, including solar radiation, air temperature, humidity, and wind speed from the FAO CLIMWAT 2.0. The full equation is shown in Equation 1.

$$ETc = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \text{(Eq. 1)}$$

where,
ETo: Reference evapotranspiration (mm d^{-1})
Δ: Slope of the saturation vapor pressure curve (kPa $°C^{-1}$)
R_n: Net radiation at the crop surface (MJ m^{-2} day^{-1})
G: Soil heat flux density (MJ m^{-2} day^{-1})
γ: Psychrometric constant (kPa $°C^{-1}$)
T: Mean daily air temperature (°C)
u2: Wind speed at 2 meters above the ground surface (m s^{-1})
e_s: Saturation vapor pressure (kPa)
e_a: Actual vapor pressure (kPa)
(e_s - e_a): Vapor pressure deficit (kPa)

Crop Water Requirement (CWR) Estimation

The estimation of crop water requirement (CWR) is primarily based on the reference evapotranspiration (ETo), which represents the evaporative demand of the atmosphere, and is adjusted by applying a crop-specific coefficient (Kc) that accounts for the physiological and morphological characteristics of the crop at various growth stages. The estimation will be conducted using Equation 2.

$$ETc = ETo \times Kc \quad \text{(Eq. 2)}$$

where,
ETc: Represents the actual water requirement of the crop (mm d^{-1}).
ETo: Indicates the water demand under standardized conditions (mm d^{-1})
Kc: Adjusts for the specific water needs of the crop based on its growth stage and characteristics.

Crop coefficient (Kc)

The crop coefficient Kc for a fully developed cocoa canopy is typically within the range of 1.0–1.05 (Allen et al., 2002). However, more detailed crop-specific coefficients, as shown in Table 3, have been proposed to account for different plantation ages, densities, and shading conditions. Based on this, a value of 1.05 was selected in the present study to represent conditions of full ground cover and shading provided by mature cocoa trees.

Table 3: Proposed Kc values for cocoa used in ETc estimation (Paredes *et al.*, 2024).

Planting stage / density	Ground cover (f_c)	Height (m)	Initial Kc	Mid-season Kc	End-season Kc
Young (< 4 years)	< 0.05	< 2.0	0.60	0.80	0.75
Medium (< 1000 plant ha^{-1})	0.50 – 0.70	2.0 – 2.5	0.90	0.95	0.95
High (1000 – 1900 plants ha^{-1})	> 0.7	> 2.0	1.00	1.05	1.05

Note: f_c = Fraction of soil surface covered by vegetation.

Statistical Analysis

Descriptive statistics, including mean, standard error (SE), and standard deviation (SD) were computed to summarize the ETc data for each site.

To assess the similarity in crop evapotranspiration (ETc) values between the two locations—Kota Kinabalu and Tawau—a statistical comparison was performed using paired sample t-test. The test was conducted at a 95% confidence level ($\alpha < 0.05$). A p-value less than 0.05 was interpreted as indicating a statistically significant difference in ETc between the two locations.

To evaluate the assumption of normality for the paired differences in ETc between Kota Kinabalu and Tawau, a Q–Q plot was generated. Normality checks were performed to ensure the appropriateness of the paired t-test. In addition, effect size was calculated using Cohen's dz to quantify the magnitude of the paired differences, complementing the statistical significance testing.

All statistical analyses were performed using Microsoft® Excel® for Microsoft 365 MSO (Version 2503 Build 16.0.18623.20208) and R-Studio (version: 2024.12.1+563), and results were interpreted accordingly.

RESULTS AND DISCUSSIONS

Reference Evapotranspiration (ETo) Trend

Figure 1 presents the monthly variation in reference evapotranspiration (ETo) between Kota Kinabalu and Tawau throughout the year. In general, both locations exhibited similar seasonal trends, with ETo values peaking during the transitional months of March to May and declining during the wetter months towards the end of the year. The highest ETo was observed in April for both locations, reaching 4.68 mm d^{-1} in Kota Kinabalu and 4.48 mm d^{-1} in Tawau. Conversely, the lowest ETo values were recorded in December.

Although the monthly ETo values between the two sites were closely aligned, slight differences were noted across several months. For instance, Kota Kinabalu consistently showed marginally higher ETo values compared to Tawau in most months, particularly from March to July.

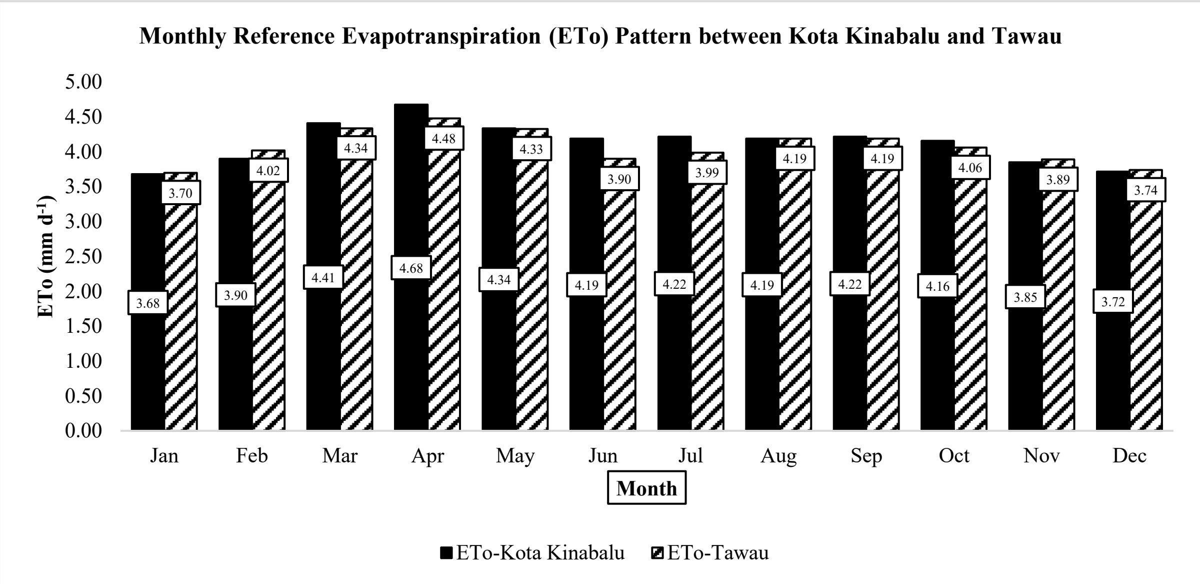

Figure 1: Comparison of monthly reference evapotranspiration (ET_O) between Kota Kinabalu and Tawau.

Crop Water Requirement of Cocoa

The crop evapotranspiration (ETc) for cocoa was estimated for both Kota Kinabalu and Tawau using the FAO CROPWAT 8.0 software with a selected crop coefficient Kc = 1.05, as presented in Tables 4 and 5, respectively.

In Kota Kinabalu, the monthly ETc ranged from 3.86 mm d^{-1} in January to a peak of 4.91 mm d^{-1} in April, with an annual average ETc of 4.34 mm d^{-1}. Similarly, in Tawau, ETc values varied from 3.89 mm d^{-1} in January to 4.70 mm d^{-1} in April, with an overall average of 4.27 mm d^{-1}.

The highest ETc values were recorded during the March to May, driven by increased solar radiation (Kota Kinabalu: 20.8, 21.8 and 19.6 MJ m^{-2} day^{-1}; Tawau: 20.3, 20.8 and 20.0 MJ m^{-2} day^{-1}) and lower relative humidity (Kota Kinabalu: 82, 81, and 82%; Tawau: 84, 84, and 85%).

Table 4: Monthly crop evapotranspiration (ET_C) for cocoa estimated using Kota Kinabalu weather data.

Month	ETo (mm d^{-1})	K_c	ETc (mm d^{-1})
Jan	3.68	1.05	3.86
Feb	3.90	1.05	4.10
Mar	4.41	1.05	4.63
Apr	4.68	1.05	4.91
May	4.34	1.05	4.56
Jun	4.19	1.05	4.40
Jul	4.22	1.05	4.43
Aug	4.19	1.05	4.40
Sep	4.22	1.05	4.43
Oct	4.16	1.05	4.37
Nov	3.85	1.05	4.04
Dec	3.72	1.05	3.91

Table 5: Monthly crop evapotranspiration (ETc) for cocoa estimated using Tawau weather data.

Month	ETo (mm d^{-1})	K_c	ETc (mm d^{-1})
Jan	3.70	1.05	3.89
Feb	4.02	1.05	4.22
Mar	4.34	1.05	4.56
Apr	4.48	1.05	4.70
May	4.33	1.05	4.55
Jun	3.90	1.05	4.10
Jul	3.99	1.05	4.19
Aug	4.19	1.05	4.40
Sep	4.19	1.05	4.40
Oct	4.06	1.05	4.26
Nov	3.89	1.05	4.08
Dec	3.74	1.05	3.93

The Significance of Crop Evapotranspiration (ETc) between Kota Kinabalu and Tawau

Table 6 showed a comparative analysis that while both locations exhibited similar seasonal trends, Kota Kinabalu generally recorded slightly higher ETc values than Tawau, particularly during the peak months from March to May. However, during mid-year (June to August) and the later months (October to December), the ETc values between the two sites converged, showing minimal differences. The mean annual ETc difference between the two locations was small (0.064 mm d^{-1}), suggesting comparable climatic influence on cocoa water requirements.

Statistical evaluation using a paired t-test ($n = 12$ pairs) confirmed that the differences in ETc between Kota Kinabalu and Tawau were not statistically significant ($t(11) = 1.72$, p-value $= 0.116$, $\alpha < 0.05$). The effect size was small-to-moderate (Cohen's dz = 0.50). The assumption of normality of differences was assessed using a Q–Q plot in Figure 2, which showed data points closely aligned with the reference line, indicating approximate normality. This indicates that despite slight monthly variations, cocoa plantations in both regions experience similar water demands, allowing for the application of similar irrigation management strategies. Nevertheless, localized adjustments may still be warranted based on specific field conditions such as soil type, canopy coverage, and irrigation system efficiency.

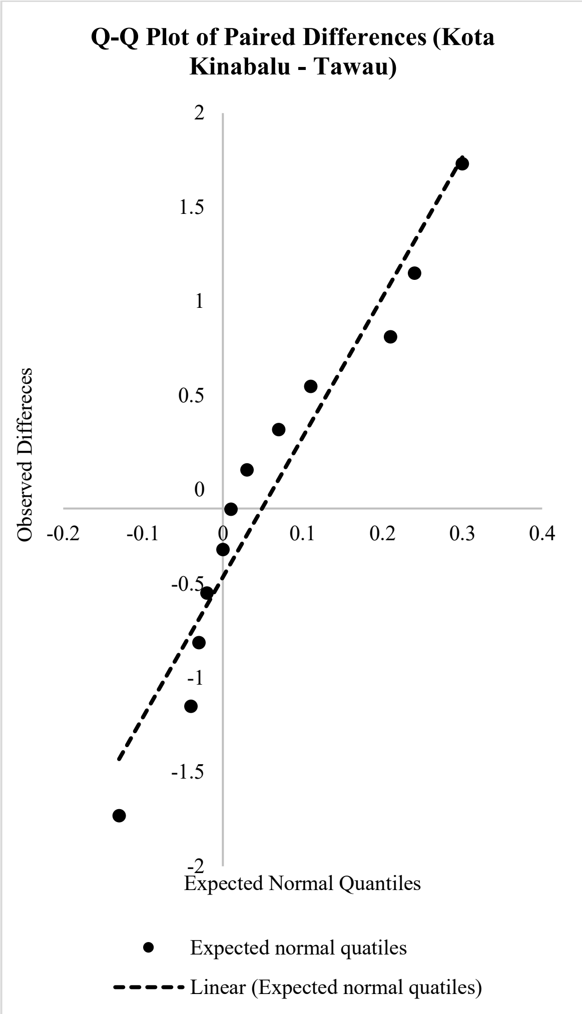

Figure 2: Q-Q plot of paired differences between Kota Kinabalu and Tawau.

Table 6: A comparative analysis of crop evapotranspiration (ET_C) between Kota Kinabalu and Tawau.

Month	ET_c-Kota Kinabalu (mm d^{-1})	ET_c-Tawau (mm d^{-1})	Difference (Kota Kinabalu – Tawau)
Jan	3.86	3.89	-0.03
Feb	4.1	4.22	-0.13
Mar	4.63	4.56	0.07
Apr	4.91	4.7	0.21
May	4.56	4.55	0.01

Jun	4.4	4.1	0.30
Jul	4.43	4.19	0.24
Aug	4.4	4.4	0.00
Sep	4.43	4.4	0.03
Oct	4.37	4.26	0.11
Nov	4.04	4.08	-0.04
Dec	3.91	3.93	-0.02
p-value, t(11) = 1.72			**0.116 NS**
Mean	**4.34**	**4.27**	**0.064**
Standard error (SE)	**0.09**	**0.07**	**0.037**
Standard deviation (SD)			**0.129**
Cohen's dz			**0.496 ≈ 0.5**

Note: The mean ET_c for Kota Kinabalu and Tawau was 4.34 ± 0.09 mm/day and 4.27 ± 0.07 mm/day, respectively. The standard error (SE) values indicate low variability in monthly ET_c across the year. A paired sample t-test revealed that the difference in ET_c between the two locations was not statistically significant (p = 0.116). NS: No significant. Cohen's thresholds: 0.2 = small, 0.5 = medium, 0.8 = large).

Estimated Irrigation Need based on Crop Water Requirement (CWR)

Table 7 presents the estimated daily irrigation requirement for cocoa trees based on monthly crop evapotranspiration (ETc) values obtained from Kota Kinabalu weather data. The estimated daily irrigation requirement was derived using Equation 3, emphasizing evapotranspiration climatic factors (temperature, solar radiation, humidity, and wind speed). Rainfall was not included in the calculation, as the analysis focused specifically on climate-driven evapotranspiration.

$$IN = ETc \quad \text{(Eq. 3)}$$

Based on an average planting distance of 3 m × 3 m (9 m² per tree) (Buku Panduan Tanaman Koko, 2012), the estimated irrigation need ranged from 34.74 L tree^{-1} day^{-1} in January to a maximum of 44.23 L tree^{-1} day^{-1} in April. The peak irrigation need corresponded with higher evaporative intensity, which was driven by increased solar radiation and reduced relative humidity, resulting in elevated ETc values. In contrast, the lowest irrigation need was observed during months of lower evaporative intensity (January and December).

These estimations provide practical guidance for irrigation planning in cocoa plantations, particularly in scheduling water application in alignment with seasonal climatic variability. The consistent range of ETc values throughout the year reflects the relatively stable tropical climate in Sabah, with only moderate month-to-month variation in water demand. Given that the statistical comparison showed no significant difference in ETc between Kota Kinabalu and Tawau, these values may also be considered applicable for Tawau.

These findings are in line with regional recommendations in other cocoa-producing regions. For instance, studies conducted in the Forest–Savannah transition zone of Ghana recommend that during the dry season, supplemental irrigation of approximately 30 liters per plant per day is effective in complementing natural rainfall and ensuring consistent productivity (Kotei, 2019). Compared to this, the irrigation needs estimated in Sabah fall within a slightly higher range, likely due to differences in canopy size, climatic demand, and estimation method. This reinforces the importance of site-specific ETc-based irrigation planning in cocoa-growing regions to optimize water use and sustain yield.

Table 7. Estimated irrigation need based on crop water requirement using Kota Kinabalu's data.

Month	**ET_c-Kota Kinabalu (mm day^{-1})**	**Estimated irrigation need (IN) (L tree^{-1} day^{-1})**
Jan	3.86	34.74
Feb	4.10	36.86
Mar	4.63	41.67
Apr	4.91	44.23
May	4.56	41.01
Jun	4.40	39.60
Jul	4.43	39.88

Aug	4.40	39.60
Sep	4.43	39.88
Oct	4.37	39.31
Nov	4.04	36.38
Dec	3.91	35.15

Note: These values represent sample estimations based on average daily crop evapotranspiration (ETc) from Kota Kinabalu and a planting distance of 3 m × 3 m for fully developed cocoa plants with full canopy cover and no rainfall (100% ETc). Since there was no significant difference in ETc between Kota Kinabalu and Tawau, this table serves as a general reference and may be similarly applied using Tawau's data where appropriate.

Application of Crop Water Requirement (CWR) in Precision Farming for the Sabah's Cocoa Industry

The application of crop water requirement (CWR) in precision irrigation for the cocoa industry holds significant promise for optimizing water use efficiency and mitigating the challenges posed by water scarcity and climatic variability.

In this study, the calculated monthly average crop evapotranspiration (ETc) for cocoa in Kota Kinabalu and Tawau was found to be 4.34 mm day^{-1} and 4.27 mm day^{-1}, respectively, a crucial metric for determining the irrigation need at different growth stages. Aligning irrigation practices with these precise irrigation need can enhance water use efficiency, ensuring that irrigation is applied in a manner that meets the crop's requirements without waste (Suhartanto & Safitri, 2020).

Furthermore, integrating this CWR-based approach with advanced technologies such as real-time data acquisition through IoT sensors can further refine irrigation scheduling. By continuously monitoring environmental parameters, these systems can dynamically adjust water delivery, thus optimizing crop growth and yield (Rajaram & Sundareswaran, 2020).

The integration of predictive models and AI-driven technologies could further enhance the effectiveness of irrigation systems. AI and machine learning algorithms can predict variations in evapotranspiration (ET) and optimize irrigation timing and volume, preventing both under- and over-irrigation (Roy *et al.*, 2024; Santosh *et al*., 2024). In the context of cocoa farming in Sabah, the use of such technologies could help adapt irrigation systems to the variable climatic conditions, ensuring that water is applied precisely when needed, thereby improving water productivity. This is particularly critical in regions where water resources are limited and erratic rainfall patterns prevail.

Additionally, the adoption of precision irrigation techniques based on CWR calculations can significantly improve water productivity and crop performance (Agele *et al.*, 2024*)*. The precision of water delivery, calibrated to the crop's actual needs, can mitigate water stress during dry periods, leading to enhanced yield and quality in cocoa production. By utilizing the calculated ETc values, cocoa farmers in Sabah, particularly in Kota Kinabalu and Tawau, can optimize their water usage, enhancing both water conservation and economic returns. Moreover, aligning irrigation volumes with actual irrigation need supports climate mitigation efforts by reducing water wastage and promoting sustainable farming practices.

CONCLUSIONS

This study estimated the crop water requirement (CWR) for cocoa in Sabah using the FAO Penman-Monteith model with climatic data from Kota Kinabalu and Tawau, applying a fixed crop coefficient (Kc = 1.05). The calculated crop evapotranspiration (ETc) values showed a relatively consistent pattern throughout the year, with the highest values occurring between March and May and an average daily ETc of 4.34 mm day^{-1} for Kota Kinabalu and mm day^{-1} for Tawau. A paired sample t-test indicated no significant difference in ETc between the two locations suggesting that a common irrigation approach may be applied across both sites. The estimated daily irrigation need for fully developed cocoa trees spaced at 3 m × 3 m ranges from approximately 35 to 44 L day^{-1} tree^{-1}. These values provide a practical guide for water management and support climate-based irrigation scheduling for cocoa cultivation in Sabah. Overall, the study highlights the relevance of ETc-based irrigation planning in optimizing water use and promoting sustainable cocoa production under tropical conditions. This approach contributes to precision agriculture practices and strengthens the resilience of cocoa farming against the impacts of climate variability in Sabah.

REFERENCES

Adet, L., Rozendaal, D. M. A., Tapi, A., Zuidema, P. A., Vaast, P., & Anten, N. P. R. (2024). Negative effects of water deficit on cocoa tree yield are partially mitigated by irrigation and potassium application. *Agricultural Water Management*, **296**: 108789–108789. https://doi.org/10.1016/j.agwat.2024.108789

Agele, S., Adejobi, K., & Ogunleye, A. (2024). Smallholder irrigation for climate mitigation and cacao (*Theobroma cacao* L.) performance improvement in the rainforest tropics. *Agricultural Sciences*. https://doi.org/10.5772/intechopen.112674

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (2002). Crop evapotranspiration: Guidelines for computing crop water requirements. Food and Agriculture Organization of United Nations. Retrieved from http://agris.fao.org/agris-search/search.do?recordID=XF1999085851

Amarkai, P. A., & Süheri, S. (2024). Comparative evaluation of crop evapotranspiration estimation methods in a semi-arid region. *Sustainability*, **16(24)**, https://doi.org/10.3390/su162411133

Buku Panduan Tanaman Koko. (2012). Taman Pertanian Universiti, Universiti Putra Malaysia. Retrieved from http://reg.upm.edu.my/eISO/docs/2012102212193130.OPR.TPU.BP.TANAMAN.Koko(9.3.2012).pdf

Food and Agriculture Organization of the United Nations. (2021). Retrieved from https://www.fao.org/land-water/databases-

Food and Agriculture Organization of the United Nations. (n.d.) Retrieved from https://www.fao.org/land-water/databases-and-software/climwat-for-cropwat/en/

Hanif, F. M. Z., Jenrry, S., & Azizul, R. S. (2024). A preliminary study on evaluation of the effectiveness of fertigation through drip and sprinkler systems for mature cocoa cultivation. *Malaysian Cocoa Journal* **16**: 19–22. Retrieved from https://mcj.koko.gov.my/ViewPDF.aspx?ID=116

Kotei, R. (2019). Influence of water levels on the yield parameters of cocoa in the forest savannah-transition zone of Ghana. *International Journal of Agriculture, Environment and Bioresearch* **04(06)** : 453-460. https://doi.org/10.35410/ijaeb.2019.4495

Olegário, K., Andrade, E., Sampaio, A., Sanchez-Matos, J., Figueirêdo, M., & Neto, J. (2022). Water scarcity footprint of cocoa irrigation in Bahia. *Ambiente E Agua-An Interdisciplinary Journal of Applied Science* **17(4)**: 1-9. https://doi.org/10.4136/ambi-agua.2840

Ortega, R., García, A., Rojas, L., & Pelayo, J. (2024). Intelligent irrigation system based on humidity and temperature predictions for cocoa crops in Piedecuesta Santander. *Research Square* https://doi.org/10.21203/rs.3.rs-4535390/v1

Paredes, P., Petry, M. T., Oliveira, C. M., Montoya, F., Ramón López-Urrea, & Pereira, L. S. (2024). Single and basal crop coefficients for estimation of water requirements of subtropical and tropical orchards and plantations with consideration of fraction of ground cover, height, and training system. *Irrigation Science*, **42(6)**: 1059–1097. https://doi.org/10.1007/s00271-024-00925-7

Rajaram, K. & Sundareswaran, R. (2020). IoT based crop-field monitoring and precise irrigation system using crop water requirement. *IFIP Advances in Information and Communication Technology*, 291-304. https://doi.org/10.1007/978-3-030-63467-4_23

Roy, S., Rathour, S., Mehta, A., Dwivedi, R., & Pandey, A. (2024). Precision water management for resource conservation in India's dryland agriculture: Strategies and technologies. *International Journal of Environment and Climate Change* **14(8)**: 464-480. https://doi.org/10.9734/ijecc/2024/v14i84367

Santosh, D. T., Anuradha, N., Kolukuluri, M., Gupta, G., Pathak, M., Krishnan, V. G., & Raghuvanshi, A. (2024). Development of IoT-based intelligent irrigation system using particle swarm optimization and XGBoost techniques. *Bulletin of Electrical Engineering and Informatics* **13(3)**: 1927-1934. https://doi.org/10.11591/eei.v13i3.6332

Suhartanto, E. & Safitri, L. (2020). Trend of changes in cocoa (*Theobroma cacao* L.) crop water producivity in D.I. Yogyakarta. *Jurnal Teknik Pertanian Lampung* **9(3)**: 237-247. https://doi.org/10.23960/jtep-l.v9i3.237-247